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6. AUTHOR(S)

Steve Gibson, Professor
Mechanical and Aerospace Engineering
University of California, Los Angeles 90095-1597
gibson@ucla.edu

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Mechanical and Aerospace Engineering
University of California, Los Angeles 90095-1597

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14. ABSTRACT
This research developed new methods for high-performance control of laser beams in high energy laser weapons and laser communications. These methods achieve optical wavefront correction, laser beam pointing and target tracking with precision levels significantly beyond those achievable by existing methods for beam control, thereby increasing the bandwidths and target distances for which beam control systems perform successfully, and expanding the classes of feasible applications. The research provided the basic theoretical analysis, algorithm development and fundamental experimental research supporting UCLA's more applied multi-disciplinary efforts on control of laser beams. UCLA's research on control of laser beams can improve the performance of directed-energy weapons such as the airborne tactical laser and the airborne laser, as well as laser communications systems used in many Air Force systems. The research employed methods of adaptive, optimal and robust control and filtering, as well as system identification.

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CONTROL, FILTERING AND SYSTEM IDENTIFICATION FOR HIGH ENERGY LASERS AND LASER COMMUNICATIONS

FA9550-09-1-0542

Steve Gibson
Mechanical and Aerospace Engineering
University of California, Los Angeles 90095-1597
gibson@ucla.edu

Tsu-Chin Tsao
Mechanical and Aerospace Engineering
University of California, Los Angeles 90095-1597
ttsao@seas.ucla.edu

Abstract

This research developed new methods for high-performance control of laser beams in high energy laser weapons and laser communications. These methods achieve optical wavefront correction, laser beam pointing and target tracking with precision levels significantly beyond those achievable by existing methods for beam control, thereby increasing the bandwidths and target distances for which beam control systems perform successfully, and expanding the classes of feasible applications. The research provided the basic theoretical analysis, algorithm development and fundamental experimental research supporting UCLA's more applied multi-disciplinary efforts on control of laser beams. UCLA's research on control of laser beams can improve the performance of directed-energy weapons such as the airborne tactical laser and the airborne laser, as well as laser communications systems used in many Air Force systems. The research employed methods of adaptive, optimal and robust control and filtering, as well as system identification.

Adaptive and Optimal Control, Filtering and System Identification for Adaptive Optics

In recent years, UCLA has established a comprehensive research program in high-performance control of laser beams for laser weapons and laser communications. This includes adaptive optics for wavefront correction as well as precision pointing and tracking in directed energy (DE) systems. The objective of adaptive optics (AO) in directed energy systems is to maximize the laser intensity at a tight spot at the center of a targeted area. UCLA researchers have developed adaptive and optimal filtering and control methods for wavefront prediction and correction to compensate for the effects of atmospheric turbulence, platform vibration and sensor noise, all of which degrade the performance of laser weapons and communication systems. Compared to the classical methods used in adaptive optics and beam steering and pointing, the methods developed at UCLA can improve the performance of directed-energy weapons such as the airborne laser (ABL) and the airborne tactical laser (ATL), as well as laser communications systems. UCLA's adaptive control methods for adaptive optics have been implemented successfully in high-fidelity wave-optics simulations of directed energy systems, as well as adaptive optics experiments at UCLA and the Starfire Optical Range at the Air Force Research Laboratory, Kirtland AFB.

Research supported partially by the current grant included theoretical, numerical and experimental investigation of adaptive and optimal filtering and control for adaptive optics. Experimental results in [1] illustrate the important performance improvements achievable with UCLA's methods for adaptive control in adaptive optics. Besides the multichannel adaptive filtering at the heart of the adaptive control scheme, a significant contribution in [1] is the new frequency-weighted spatial modes for representing optical wavefronts in the actuator space associated with the deformable mirror and the sensor space associated with the self-referencing interferometer used as a wavefront sensor.

A related current research topic supported partially by AFOSR was linear time-invariant (LTI) minimum-variance prediction and control of wavefront aberrations in adaptive optics. This is a computationally less complex alternative to adaptive control, which yields comparable performance in a range of applications. While LTI optimal control requires much less real-time computation in adaptive optics than fully adaptive control, obtaining wavefront predictor that is the heart of the LTI controller is a challenging mathematical and computational problem in off-line or quasi-adaptive system identification. The main novelty and challenge here is the need to capture both the spatial and temporal information in the turbulene-induced optical wavefronts in a form that is most useful for wavefront control. This form is a state-space predictor, which is identified from measured wavefront sequences. Recent research has demonstrated that,

although this state-space predictor has a very different mathematical structure from the classical mathematical models of turbulence-induced optical wavefronts, the new prediction model captures the spatial-temporal characteristics of the original wavefronts. Generating these state-space models requires system identification with much larger numbers of data channels and states than have been typical in other areas of system identification for control. UCLA's adaptive subspace system idenfication methods have proved effective for solving this system identification problem. One topic of current research is the derivation of intelligent order-determination criteria needed to make the system identification quasi-adaptive for on-line updating of the optimal controller.

The system identification and wavefront prediction methods developed in this research have been employed in an Air Force SBIR awarded recently to MZA Associates Corp. for spatial-temporal control in adaptive optics.

Mitigating the Effects of Sensor Noise and Control Constraints

In [2], we introduced a frequency weighting approach for adaptive control of laser beam jitter. The method was developed to solve a phenomenon that we observed in beam control experiments with high levels of high-frequency sensor noise. These UCLA experiments and the new frequency-weighting method are described in [2]. In the experiments, high-bandwidth jitter control is made much more difficult by two realistic features: high-frequency noise on the optical sensor and electrical-current saturation in the fast steering mirror used as control actuator. The frequency weighting approach to adaptive jitter control also has proved essential in a recent transition reported in [3].

It should be noted that our new frequency-weighting method for adaptive control differs substantially from the frequency weightings historically used in optimal and robust LTI control design. An important difference is a rather counter intuitive design: to prevent the adaptive controller from amplifying high-frequency sensor noise, the tuning signal is passed through a high-pass weighting filter, [2]. This method worked far better than any adaptive controller employing a low-pass filter to mitigate the effects of high-frequency sensor noise.

The correctness of this new approach was verified by analysis, as well as numerous simulations and laboratory experiments and the recent field tests reported in [3]. However, research is needed to develop a systematic method for selecting the order and bandwidth of the high-pass weighting filter. This method should take into account the statistics of the noise, the saturation limits on the control signal, as well as the plant dynamics. Our first objective in this part of the research is a systematic on-line method for selecting the weighting filter. After that, we sought an adaptive algorithm for

selecting the weighting filter so that the overall adaptive controller can track changing disturbance and sensor noise to maintain optimal performance.

In addition to frequency weighting, an equally important tool for providing the robustness required for real applications of adaptive jitter control in high-performance optical systems is optimal selection of the variable-order of the adaptive filter at the core of the controller. Current research is exploiting the order-recursive structure of UCLA's adaptive lattice filters to develop methods for optimal order selection in variable-order adaptive control. Optimal order selection requires real-time statistical analysis of several internal error signals associated with multiple filter orders.

A transition was performed under an SBIR to Tempest Technologies funded by the Missile Defense Agency (MDA) and the High Energy Laser Joint Technology Office (HEL JTO). The location is The High Energy Laser Systems Test Facility (HELSTF) at the White Sands Missile Range, NM, operated by the U.S. Army Space and Missile Defense Command/Army Forces Strategic Command. In this field test, UCLA's adaptive jitter control methods are being applied to minimize track error in the Advance Pointer Tracker. The track error is the displacement of a target image on a real-time tracking camera, which acquires the image from the telescope shown in Figure 1. The primary source of jitter is the telescope gimbal. Figure 2 shows the track error time series plots from one of several recent experiments. The adaptive controller augments the existing classical track loop already in place for the tracking telescope. Figure 2 shows the significant improvement in track errors after the adaptive control loop closes at 60 sec. More results and the experiment are discussed in detail in [3].

Figure 1. Advanced Pointer Tracker, White Sands Missile Range.

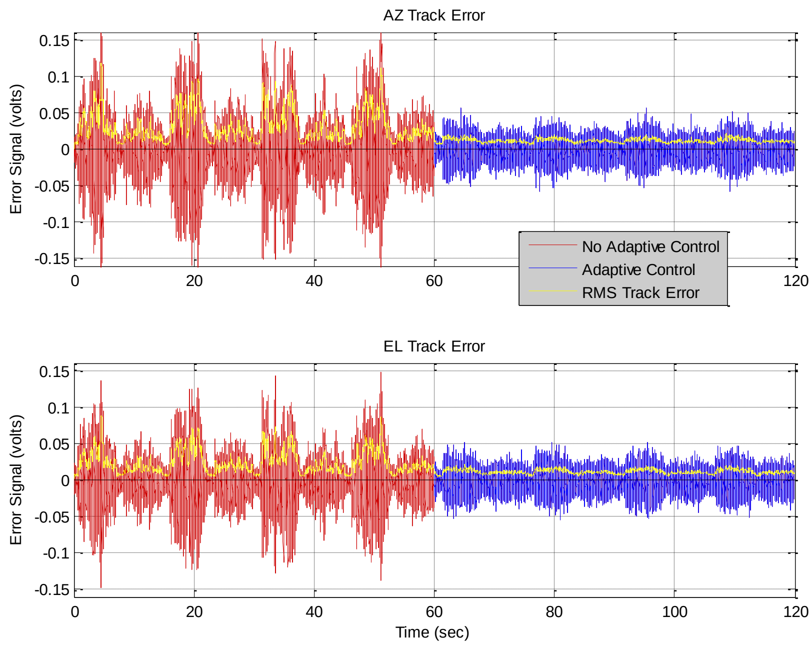

Figure 2. Azimuth and elevation track errors for horizontal circular target motion. Adaptive control begins at 60 sec.

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[3] Steve Gibson, Tsu-Chin Tsao, Dan Herrick et al., “Adaptive jitter control for tracker line of sight stabilization,” SPIE Optics+Photonics, San Diego, CA, August 2010.

[4] N. O. Perez Arancibia, J. S. Gibson, and T.-C. Tsao, “Observer-Based Intensity-Feedback Control for Laser Beam Pointing and Tracking,” *IEEE Transactions on Control Systems Technology*, Vol. 20, No. 1, January 2012.

Personnel Supported During Duration of Grant

Salman Monirabbasi	Ph. D. Student, University of California, Los Angeles
Nestor Perez Arancibia	Ph. D. Student, University of California, Los Angeles
Steve Gibson	Professor, University of California, Los Angeles
Tsu-Chin Tsao	Professor, University of California, Los Angeles

Publications

Salman Monirabbasi and Steve Gibson, “Adaptive control in an adaptive optics experiment,” *Journal of the Optical Society of America A*, Vol. 27, No. 11, November 2010.

Steve Gibson, Tsu-Chin Tsao, Dan Herrick et al., “Adaptive jitter control for tracker line of sight stabilization,” SPIE Optics+Photonics, San Diego, CA, August 2010.

N. O. Perez Arancibia, J. S. Gibson, and T.-C. Tsao, “Observer-Based Intensity-Feedback Control for Laser Beam Pointing and Tracking,” *IEEE Transactions on Control Systems Technology*, Vol. 20, No. 1, January 2012.

Ph. D. Thesis

Salman Monirabbasi, “Adaptive control of turbulence-induced wavefront errors in Adaptive Optics,” Ph.D. thesis, University of California, Los Angeles (2009).

AFRL Point of Contact

Dr. Dan Herrick, Kirtland AFB, NM, 505-853-5189. Numerous meetings at Kirtland AFB and White Sands Missile Range.

Transitions

The methods developed in this research for adaptive control of optical jitter have been used in the Advanced Pointer Tracker at the High Energy Laser Systems Test Facility (HELSTF) at the White Sands Missile Range, NM, operated by the U.S. Army Space and Missile Defense Command/Army Forces Strategic Command. A transition is being performed under an SBIR to Tempest Technologies, Los Angeles, CA, funded by the Missile Defense Agency (MDA) and the High Energy Laser Joint Technology Office (HEL JTO) under the direction of AFRL. Points of contact: (AFR) Dr. Dan Herrick, Kirtland AFB, NM, 505-853-5189, (Tempest Technologies) Dr. Yun Wang, 310-216-1677.

The methods developed in this research for system identification and wavefront prediction are being employed in an Air Force-sponsored SBIR to MZA Associates Corporation, Dayton, OH, for spatial-temporal control in adaptive optics. Point of contact: Dr. Matthew Whiteley, 937-684-4100 x101.